Web Resume: James G. Berryman

Jim Berryman joined LBNL as a Geological Senior Scientist in 2006. Prior to that, he was a physicist and researcher at Lawrence Livermore National Lab for 25 years and also in industry for 4 years (at CONOCO and then Bell Laboratories). His Ph.D. is in Condensed Matter Physics (U. Wisc. – Madison, 1975). He has held visiting, consulting, and sabbatical appointments at various universities, including Stanford (Geophysics) and NYU (Courant Institute). He has expertise in the physical properties of rocks and porous materials, as well as in inverse theory and mathematical geophysics. He has authored over 150 journal articles, a comparable number of conference proceedings papers and company internal reports, holds four patents, and was honored with *2005 Biot Medal* by Am. Soc. Civil Engng. for his contributions to the theory of poroelasticity. The Society of Exploration Geophysicists and the American Physical Society have both recently named him an Outstanding Referee of submitted technical papers.

Since 2006, Berryman's Basic Energy Sciences supported research work and publications have been concentrated primarily on clarifying how the influence of fractures in earth reservoirs can be quantified in relatively easy-to-use effective medium theories. These results have made extensive use of the ideas and methods due to Kachanov (1980), which also form the basis of later (and often quoted) work by Sayers and Kachanov (1991). Berryman has developed rigorous connections between these theories and poroelasticity theory during this period, both for overall isotropic systems and more recently for anisotropic systems (up to orthotropic symmetry). The studied class of orthotropic systems includes all the ones most commonly considered and studied by seismologists, including TI (transversely isotropic), HTI (horizontally TI), VTI (vertically TI), and TTI (tilted TI). One general and fundamental result coming out of the work is that the influence of fluids in fluid-saturated fractures is to decrease the compliance (i.e., increase the stiffness) possessed by the fractured reservoir without these fluids, and in a very predictable fashion. The result is that the difference between saturated (undrained) reservoir compliance and unsaturated (drained but fractured) reservoir compliance is reduced by a definite factor of $(1-B)$, where B is the well-known Skempton coefficient from soil mechanics. The factor B depends on grain bulk modulus, fluid modulus, porosity, and drained bulk modulus of the fractured system itself, and is also a directly measurable quantity. The $(1-B)$ factor multiplies all the fracture-influence elastic compliance parameters appearing in the Sayers and Kachanov (1991) fracture analysis approach to the effective medium theory.

Closely related ideas -- concerning inversion of the poroelasticity equations so that drained (unsaturated) constants can be deduced when undrained (saturated) constants have been measured -- have recently been applied to the laboratory ultrasonic data of Nakagawa (LBNL) on granular systems under pressure, including two types of sand grains and one glass bead sample. It was established in this work that the drained constants can all be deduced from the measurements using an analytical inversion method. The paper summarizing this work has been accepted for publication in Journal of the Acoustical Society of America and should appear in March or April, 2010.

Another theme of Berryman's recent research has been the mechanics of fractured or granular systems under stress, but without the added complication of saturating fluids. In collaborative work with Pride (LBNL), an analytical theory of granular systems that are not close-packed has been developed. Loosely packed granular systems (by definition) often have some percentage of their particles that are not fully constrained by their surrounding particles, and so are called rattlers. As stress is applied to a packing, the rattlers become jammed and cause the elastic moduli to increase with increasing stress faster than the usual Hertz-Mindlin and/or Walton (1987) models for close packed systems. A theory of rattler jamming was developed by Pride and Berryman that appeared in *Acta Mechanica* early in 2009, and that provides good fits to laboratory data of the pressure dependence of elastic moduli for such systems.

In collaborative work with A. Aydin (Stanford) on structural geology applications of the Sayers and Kachanov (1991) fracture analysis methods in effective medium theories, Berryman was able to show (albeit very approximately) what are the expected modes of failure for some very complicated fractured systems, and to make some predictions of the fracture densities at which these failures could be expected to occur. Although the method was conceptually quite simple, it turned out to be somewhat tedious to implement. Nevertheless, the results agreed reasonably well with observed fracture densities seen in actual field outcrops. Further work along these lines – including detailed comparisons to field data -- will be needed to establish if the approach is viable in a wide class of such applications. Work including applications to fluid flow is also planned.

In related work on seismic wave propagation in anisotropic earth systems (but without any particular emphasis on the source of the anisotropy), Berryman (2008) showed how to extend the well-known Thomsen (1986) weak anisotropy formulation of exploration seismic reflection analysis to the case when anisotropies are stronger, and the field acquisition plan includes wide surface source-receiver offsets, and therefore wide incidence angles for reflected seismic waves. The observed difficulty with Thomsen's weak anisotropy formulation is that vertically polarized shear waves are predicted by this scheme always to have a peak or a trough in wave speed at incidence angles of exactly 45 degrees. However, in real anisotropic systems, these peaks or troughs must instead appear at some other angle. Having a peak or trough at 45 degrees incidence angle is actually impossible. This issue arises in practice because Thomsen's original formulation was developed at a time when incidence angles were usually limited by then current technology to about 15 degrees, and then this issue never arises in practice. The new formulas are slightly more tedious (i.e., complicated) than those of the original Thomsen (1986) formulation, but otherwise should cause little difficulty in terms of practical implementation since everything needed is given explicitly in the published paper in *Geophysics.*

Jim continues to work on problems in rock and reservoir poroelasticity as well as seismic and electromagnetic wave inversion problems, typically but not exclusively, for applications in oil and gas exploration and exploitation. Other geophysical applications include mechanisms of induced seismicity for geothermal energy and CO2 sequestration.

RECENT BERRYMAN PUBLICATIONS (2006-2009):

JGB and S. Nakagawa, "Inverse problem in anisotropic poroelasticity: Drained constants from undrained ultrasound measurements," *J. Acoust. Soc. Am.*, to appear 3-4/2010.

JGB, "Poroelastic measurement schemes resulting in complete data sets for granular and other anisotropic porous media," *Int. J. Engng. Sci.,* online Dec. 16, 2009.

JGB and A. Aydin, "Quasi-static analysis of elastic behavior for some higher density crack systems," *IJ Num. Anal. Meth. Geomech.*, online Dec. 15, 2009.

Attila Aydin and JGB, "Analysis of growth of strike-slip faults using effective medium theory," *J. Struct. Geol.*, online Nov. 27, 2009.

S. R. Pride and JGB, "Goddard rattler-jamming mechanism for quantifying pressure dependence of elastic moduli of grain packs," *Acta Mech.* ***205*** (1-4), 185-196 (2009).

JGB, "Frequency dependent thermal expansion in binary viscoelastic composites," *Mech. Mat.* **41** (4), 463-480 (2009).

JGB, "Aligned vertical fractures, HTI reservoir symmetry and seismic anisotropy parameters for polar media," *Geophys. Prosp.* **57** (2), 193-208 (2009).

H. H. Liu, J. Rutqvist, and JGB, "On the relationship between stress and elastic strain for fractured rock," *Int. J. Rock Mech.* **46** (2), 289-296 (2009).

JGB, "Elastic and transport properties in polycrystals of cracked grains: Cross-property relations and microstructure," *Int. J. Engng. Sci.* **46** (6), 500-512 (2008).

JGB, "Exact seismic velocities for transversely isotropic media and extended Thomsen formulas for stronger anisotropies," *Geophysics* **73** (1), D1-D10 (2008).

G. Block, M.B. Rubin, J. Morris, and JGB, "Simulations of dynamic crack propagation …," *Int. J. Fracture* **144**, 131-147 (2007).

JGB, "Seismic waves in rock with fluids and fractures," *Geophys. J. Int.* **171** (2), 954-974 (2006).

JGB and V. Grechka, "Random polycrystals of grains containing cracks: Model of quasistatic elastic behavior for fractured systems," *J. Appl. Phys.* **100**, 113527 (2006).

JGB, "Measures of microstructure to improve estimates of elastic constants and transport coefficients," *Mech. Mat.* **38** (8-10), 732-747 (2006).

JGB, “Effective medium theories for multicomponent poroelastic composites,” *ASCE J. Engng. Mech.* **41** (4), 519-531 (2006).

JGB, “Estimates and rigorous bounds on pore-fluid enhanced modulus in poroelastic media with hard and soft anisotropy,” *Int. J. Damage Mech.* **15** (2), 133-167 (2006).

SHORT BIBLIOGRAPHY OF SOME OLDER, HIGHLY CITED PAPERS:

S. R. Pride, J. G. Berryman, and J. M. Harris, Seismic-wave attenuation due to wave induced flow*, J. Geophys. Res.* **109**, B01201 (2004).

S. R. Pride and J. G. Berryman, Linear dynamics of double-porosity dual-permeablity materials. I. Governing equations and acoustic attenuation, *Phys. Rev. E* **68**, 036603 (2003).

J. G. Berryman and H. F. Wang, The elastic coefficients of double-porosity models for fluid transport in jointed rock, *J. Geophys. Res.* **100** (B12), 24611-24627 (1995).

J. G. Berryman, Single-scattering approximations for coefficients in Biot’s equations of poroelasticity, *J. Acoust. Soc. Am.* ***91***, 551-571 (1992).

J. G. Berryman, Effective stress for transport properties of inhomogeneous porous rock, *J. Geophys. Res.* **97**, 17409-17424 (1992).

J. G. Berryman and G. W. Milton, Exact results for generalized Gassmann’s equations in composite porous media with two constitutents, *Geophysics* **56**, 1950-1960 (1991).

J. G. Berryman, Random close packing of hard spheres and disks, *Phys. Rev. A* **27**, 1053-1061 (1983).

J. G. Berryman, Confirmation of Biot’s theory, *Appl. Phys. Lett.* **37**, 382-384 (1980).

J. G. Berryman, Long-wavelength propagation in composite elastic media II. Ellipsoidal inclusions, *J. Acoust. Soc. Am.* **68**, 1820-1831 (1980).

J. G. Berryman, Long-wavelength elastic anisotropy in transversely isotropic media, *Geophysics* **44**, 896-917 (1979).